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ANNUAL PROGRESS REPORT NO. 93

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Joint Services Contract

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AFOSR76-3073	T.T. Wu
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NSF ENG-75-14455	T.T. Wu
NSF ENG-76-17596	T.T. Wu
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NSF DMR-77-24295	H. Ehrenreich
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NSF DMR-79-04155	M. Tinkham
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DOE-DE-AC03-79-ET-23037	W. Paul
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I.1 Electronic Theory of Disordered Semiconductors. C.D. Gelatt and S. Kivelson, Contracts N00014-75-C-0648 and NSF DMR77-24295; Research Unit 1.

With the departure of both contributors of this project from Harvard, this phase of the research activity has been terminated. The three papers cited in the preprint form last year have now appeared.[1,2,3] The results of this work were described in last year's report. Kivelson and Gelatt[4] have also considered photoluminescence in amorphous Si. They have

constructed a simple phenomenological model of the electronic structure of the pseudogap of an amorphous semiconductor and used the processes that are known to determine the nature of the photoluminescence as a starting point for a systematic investigation of this phenomenon. The results are applied to amorphous Si. Many of the most striking features of these results appear to derive straightforwardly from the nature of the primary luminescing entity, a "trapped exciton" in which the hole is trapped at localized gap state and the electron is bound to the hole by their mutual Coulomb attraction. Other important properties reflect the dynamics of the hopping motion of a charge carrier through a band of localized states. The model presented is sufficiently general that some, if not all, of the results could apply to other amorphous semiconductors as well.

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I.2 Interfaces. A. Carlsson and H. Ehrenreich, Contract N00014-75-C-0648; Research Unit 1.

The aims of the theoretical research program concerning interfaces is to develop the understanding of the electronic structure in idealized models in order to shed light on problems associated with improving the performance of electronic semiconductor heterojunctions. A deeper understanding of the microstructure and electronic structure of grain boundaries is also of great potential importance, particularly in connection with photovoltaic devices.

At present the relevant experimental data is still rather sparse: for example, information concerning Schottky barriers consists mainly of barrier height measurements as a function of metal layer thickness. The experimental evidence is also somewhat circumstantial in semiconductor hterojunctions in which the density of interface states can be estimated directly from their electrical properties. Interface states of course are all important in determining whether a given layer of insulating material is able to passivate a semiconductor device.

One of the aims of the interface program therefore has been to establish the conditions under which localized states are present at semiconductor interfaces and to clarify the nature of these states. Emphasis has been on the study of simple models since the microstructure present at a realistic interface involving given materials has not been sufficiently well characterized. The derivation of criteria that must be satisfied by the parameters in tight-binding interface models suggest that previous semiconductor heterojunction calculations performed using the empirical tight-binding method may underestimate the density of interface states. The electronic structure of the interface between a tight-binding semiconductor and a jellium model has also led to new insights concerning the densities of states.

In order to permit calculations of the electronic properties of such diverse systems as Green's function formalism which includes self-consistency in an approximate way has been formulated by including a short range potential on the atomic planes immediately surrounding the interface it also permits the approximate inclusion of the effects of molecular clusters, which have been observed in interfaces involving Si and Pd interfaces.

This formalism has been used for a variety of purposes besides those already mentioned. For example, the results for a Heine-Weaire model semiconductor and cubum metal interface show two bands of true interface states in a small portion of the Brillouin zone parallel to the interface, which are strongly localized on the two atomic layers next to the interface. The tails of metal way functions provide additional interface states. The Schottky barrier height depends linearly on the metal work function.

While these calculations may bear only a qualitative relation to reality, they should nevertheless serve to provide a measure of the complexity to be expected in a relatively simple abrupt interface and provide insight through comparison with experimental data whether such models are really warranted or not.

I.3 Laser-Induced Disequilibrium in Superconducting Films. A.D. Smith, L.N. Smith, W.J. Skocpol, and M. Tinkham, Contract N00014-75-C-0648, and NSF Grant DMR 79-04155; Research Unit 2.

We have published a description[1] of our experimental investigations of the inhomogeneous dissipative state of current-carrying superconducting microstrips under optical illumination.[2] The laser illumination raises the apparent temperature of the strip at low intensities, but causes noticeably

more broadening of the current-voltage characteristics at higher intensities, due either to residual inhomogeneities of the illumination or to an intrinsic inhomogeneity of the uniformly illuminated state. No evidence was found for any first order transitions in the strip. We have further investigated the low intensity regime by the unfolding of precise tunneling data from weakly illuminated Al-PbBi tunnel junctions.[3] This experiment confirms that the nonequilibrium quasiparticle populations generated by the illumination are well described by a simple T^* model.

While measuring these nonequilibrium quasiparticle populations in laser illuminated films, we discovered asymmetries of the I-V curves that suggest that a small photocurrent flowed across the Al-PbBi junctions independent of the bias voltage. We are now using a SQUID galvanometer to measure this current directly, and are developing a theoretical model to interpret the observed current in terms of the differential nonequilibrium populations and an energy-dependent tunneling probability.

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I.4. Nonequilibrium Switching Phenomena. D.J. Frank, W.J. Skocpol, and M. Tinkham, Contract N00014-75-C-0648; Research Unit 2.

We are investigating the time scale for the appearance of a voltage drop along superconducting microstrips when their critical current is suddenly exceeded. We have developed a theoretical approach based on ideas about dynamic "cooling" effects (discussed in a more general review[1] and applied to the dynamics of superconducting weak links[2]) which may explain the 10-100 nsec time scales observed in Al microstrips by Pals and Wolter[3] and by us.

We have also helped to design, in collaboration with IBM Watson Research Center, Josephson junction pulse generators and sampling circuits to be fabricated by IBM which will allow us to extend these measurements to other materials in which switching times of the order of 100 picoseconds would be expected on the basis of our theory.

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I.5 Low Frequency Noise Properties of Superconducting Point Contacts. G. Blonder, W.J. Skocpol, and M. Tinkham, Contracts N00014-75-C-0648 and N00014-76-C-0032; Research Unit 2.

We are investigating the low-frequency noise which limits the sensitivity of Josephson point contact radiation detectors. We have measured the noise spectrum in the range 0.03 Hz - 10 kHz for Ta-Ta point contacts biased at various voltages. The observed noise is much larger than that expected from Hooge's empirical relation for $1/f$ noise in normal-metal contacts, and has an approximate $1/f^2$ dependence at high voltages (well above the gap). At lower voltages the magnitude is smaller and the frequency dependence is more nearly $1/f$. Experiments testing certain possible origins of the noise are underway.

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I.6 Production and Characterization of Amorphous Semiconductors. D.A. Anderson, J. Blake, P. Ketchian, D.K. Paul, and W. Paul, Contracts N00014-75-C-0648, NSF DMR78-10014, and NSF DMR77-24295; Research Unit 3.

Amorphous semiconducting films of Ge, Si, $Ge_{1-x}H_x$ alloy, $Si_{1-x}H_x$ alloy, GaAs, and $(GaAs)_{1-x}H_x$ alloy have been produced by r.f. sputtering of polycrystalline targets by argon onto substrates of Be, 7059 glass, crystalline Si and Al held at suitable temperatures between 0°C and 400°C. Variation of the partial pressure of Ar was done to alter the conditions in the plasma so as to change the deposition rate and the surface mobility of the depositing Si atoms. Variation of the substrate temperature permitted

healing of the disordered network without inducing crystallization. Variation of the partial pressure of H both permitted studies of variable composition alloys and exploration of the possible different H-configurations incorporated. Addition of PH_3, B_2H_6, N_2 or O_2 to the sputtering gas permitted doping the semiconductor n or p-type and the formation of n-p junctions.

The films are characterized chemically, when required, by electron microprobe and sputter-ion analysis. X-ray examinations are conducted to ensure amorphicicty, the density is determined by floating the sample in a liquid whose density may be varied and accurately measured, and the thickness is found using a Sloan Dektak profiling apparatus.

The films produced have been used for measurements of transport, phototransport, photoluminescence, optical absorption, electroreflectance, and field effect. A coherent self-consistent explanation of these data has been sought. In subsequent sections, only those measurements supported predominantly by the JSEP will be described.

I.7 Study of Conditions for the Optimum Configuration of Pseudogap States in Amorphous $Si_{1-x}H_x$ Alloys. D.A. Anderson, E.C. Freeman, G. Moddel, S. Oguz, M.A. Paesler, P. Viktorovich, and W. Paul, Contracts N00014-75-C-0648, NSF DRM78-10014, and NSF DMR77-24295; Research Unit 3.

In last year's report, we emphasized that "optimum configuration" depended on the end in view, whether maximum photoconductivity, maximum photoluminescence, or maximum solar cell efficiency. The idea that "optimum" automatically meant the lowest density of pseudogap states attributable to defects or impurities was simplistic. Thus, for example, displacement of

the Fermi level (by altered conditions of preparation) from the center of the pseudogap toward the conduction band appears to improve the photoconductive response, even when other measurements suggest that the total density of defect/impurity related states in the gap has increased. (An explanation of this result in the literature suggests that the increase in photoconductive response is attributable to a decrease in the total density of recombination centers available to the electrons.) This year, apart from forays to maximize this or that property, we have in fact concentrated on trying to produce material with the lowest pseudogap state density. It is generally assumed that low gap state density is a necessary, although not sufficient, condition for high room temperature resistivity and ease of doping n or p type, and that such properties are necessary (inter alia) for xerographic, vidicon and solar cell applications.

The principal sputtering parameters are judged to be substrate temperature, T_s; partial pressure of hydrogen, p_H; partial pressure of argon, p_{Ar}; r.f. power, and substrate D.C. bias. In addition to these, the base vacuum is one measure of the freedom of the system, and the films produced, from potential contamination by water vapor, air-leaks, etc. Finally, the pre-sputtering treatment of target, substrates, and the interior of the deposition system is judged to be of potential importance in the elimination of contaminants which might increase the pseudogap state density.

Evaluation of the results of variations of these deposition conditions is done through study of the impurity concentrations and impurity profiles (by secondary ion mass spectroscopy); hydrogen content (nuclear reactions with ^{15}N); TEM and SEM studies; and measurement on co-deposited samples of variations in the conductivity, thermopower, absorption edge, vibrational

absorption, H-evolution, photoconductivity, photoluminescence, field-effect and capacitance-frequency dependence in Schottky barrier structures. A detailed discussion of these results is not appropriate here, but the conclusions can be given in summary form.

1. Substrate temperature T_s. We have concentrated on rather high values of T_s (up to 400°C) so as to obtain the highest healing effect at the growing surface. It appears, however, that the results do not differentiate among samples produced between T_s of 250°C and 400°C, presumably because any additional healing effects that do occur are small compared to the changes that are possible in the other deposition parameters as a result of the increased T_s.

2. Partial pressure of hydrogen, p_H. We have tried to keep the hydrogen partial pressure as low as is consistent with compensation of dangling bonds. It will be recalled from last year's report that the incorporation of H is not linear in p_H. Films produced at high p_H (say ≥ 4 mTorr) may have the same H-content as those produced near 1 mTorr, but they appear to have a higher density of gap states. In general terms, the H-configurations incorporated at high p_H, and the corresponding defect configurations, are supposed to be different from those in low p_H films.

It is evident from the results that *very* low p_H, say below 10^{-4} Torr, while giving samples with H-contents up to about 10 atomic percent, do not lead to the lowest gap state densities (estimated from measurements of capacitance versus frequency, C(w); see I.8, supported by measurements of photoconductivity and photoluminescence). It is notable that the atomic percentage of H is far greater than the integrated density of states in the gap of unhydrogenated a-Si. This points up the so-far-unsolved problem of H-compensation of defects: How to accomplish this desirable end without alteration of the material from a-Si to a-Si-H alloy?

The lowest pseudogap density of states is found for p_H in the range of 1 mTorr or greater, again as measured by $C(w)$. Strictly speaking, the $C(w)$ measurements give an estimate of the state density within 0.1 eV of the Fermi level, and there is no reason to suppose this energy corresponds always to the minimum in the state distribution. The lowest state density from $C(w)$ is 5×10^{15} $cm^{-3}eV^{-1}$, a value equal within experimental uncertainties to the lowest value found for a-$Si_{1-x}H_x$ alloys produced from silane by glow discharge. For these samples, T_s is in the range 250-400°C, p_{Argon} in the range 5-15 mTorr, the sputtering power 200 watts or about 2 watts/cm^2 of target, and the deposition rate about 1-2 Å|s.

3. Partial pressure of argon, p_{Argon}. A special study was reported last year of the result of varying the partial pressure of argon used in the deposition, based on the notion that an optimum pressure existed: too low an argon pressure would lead to highly energetic Si atoms and ions striking the growing film, causing excessive (and unannealed) damage, because the mean free path of the depositing species was too long; on the other hand, too high an argon pressure would lead to fluffy, low density, porous films, because the incident species had such a low momentum that they could not brush "debris" or poorly connected complexes off the growing surface. The study was very successful, and clearly established optimum partial pressures of argon for our other deposition conditions.

4. R.f. power and substrate d.c. bias. Very few experiments on varying the r.f. power and substrate d.c. bias were done, but both are planned for the next report period.

Extensive study was made of the results for the incorporation of C, N and especially O of pre-sputter (of films) bombardment of both target and substrate by N and A ions. Bombardment by N was undertaken because it

was felt that reactions with adsorbed species (including H_2O) would lead to their elimination. Subsequent bombardment with A was meant to ensure that the N itself was not left in the target or on surfaces near the substrates. The principal direct evaluation procedure was SIMS, which showed that a combination of N and A pre-sputter bombardments did reduce the contaminant density throughout the bulk of the film. However, pre-sputter bombardment of the substrate platform turned out to be a risky and questionable procedure, since contaminants could apparently be detached but not eliminated, and this led to an observed increased contaminant density near the substrate-film interface. Such a high local density of other species may pose difficulties for the measurement of field effect (see I.8 below).

During this report period, no definitive correlation was made between the impurity content of the films and the measured properties which depended on the pseudogap density of states. Although the content of O, N and C is high compared to that in crystals, it may be argued that these impurities do not lead to gap states.

I.8 Use of the Field Effect, C(w) Measurements and Low Photon Energy Photoconductivity to Determine the Pseudogap State Density in Amorphous $Si_{1-x}H_x$ Alloys. D.A. Anderson, G. Moddel, P. Viktorovich, R. Weisfield, and W. Paul, Contracts DOE-DEAC0379-ET-23037 and N00014-75-C-0648; Research Unit 3.

During the latter half of this report period only the Department of Energy supported the measurements of field effect and capacitance-voltage. The following conclusions have been drawn from this program.

(1) The early reports of field effect measurements in the literature did not reveal difficulties in the preparation of samples and the application of fields, which now appear to be a usual occurrence.

(2) The early analyses did not reveal ambiguities in interpretation which are now acknowledged generally to lead to non-unique densities of states, depending on the assumptions made, from the same experimental data.

Our experience has told the following.

(1) A high density of interface states between the quartz substrate and the a-$Si_{1-x}H_x$ alloy prepared by sputtering often prevents the determination of the bulk density of states from field effect. This density of interface states is lower in samples prepared by glow discharge in our laboratory, even when the bulk densities of states in sputtered and glow discharge samples are equal, as revealed by C(w) measurements. The origin of the large density of interface states is unidentified, but it is more likely to be connected with defects caused by bombardment than by contamination, since the conditions of cleanliness of our sputtered material are superior to those for the glow discharge samples.

(2) Measurements of C(w) on Schottky barrier structures made from sputtered material are interpreted to give bulk state densities at least as low as in any glow discharge material. At the moment of writing, this is our preferred method of determination of state densities.

(3) Measurements of the spectral dependence of photoconductivity at low photon energies can be used, if properly normalized by direct measurements of absorption coefficient at higher energies to determine the absorption spectrum down to absorption coefficients below 1 cm^{-1}. These spectra can then be interpreted, with some plausible assumptions, in terms of single electron densities of states in general agreement with those found from C(w).

I.9 Photoconductivity in Amorphous $Si_{1-x}H_x$ Alloys. D.A. Anderson, G. Moddel and W. Paul, Contracts N00014-75-C-0648; Research Unit 3.

Measurements of the dependence of photoconductivity on the photon energy, the illumination intensity, and the temperature, for samples prepared under a variety of conditions, have been continued. The deposition parameters maximizing the photoconductive response have been mapped out and fit into a self-consistent scheme. The low photon energy absorption spectrum has been deduced under a limited set of assumptions, whose validity has been critically examined and verified. From the magnitude of photoconductivity and its decay after illumination is removed, the trap limited drift mobility has been established. The variation of this mobility with conditions of preparation has been studied.

The dependence of the photoresponse on doping, or more generally on variation of the position of the Fermi level by doping on variation of the deposition parameters, has been studied. Finally, a collaboration with the University of Montreal on the determination of the drift mobility by direct time-of-flight techniques has been continued, and the temperature dependence of that (dispersive transport) trap limited mobility has shown interesting new effects.

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I.10 Forced Thermal Diffusivity Studies in Smectic Liquid Crystals. D.B. Carlin and P.S. Pershan, Contracts N00014-75-C-0648, NSF DRM76-22452, and NSF DMR77-24295; Research Unit 4.

We are developing a system, based on the forced Rayleigh scattering technique, previously used in this laboratory for studies of multilamella lipid samples,[1] to measure thermal diffusivity in smectic liquid crystals. Since the thermal conductivity is not expected to have significant critical variations, critical properties of the thermal diffusivity will be dominated by the specific heat. This appears to be the only practical possibility for measuring the heat capacity of thin films. Recent advances in the theory of melting of two-dimensional liquid crystals[2] have created the need for experimental determinations of critical phenomena in such systems. Based on our measurements of optical absorption coefficients and sample stability, we have chosen to use 40.8 near the A-B phase transition for our studies. Much of our effort during the past several months was spent in the repair and modification of certain of the electronic devices required in this experiment. Timing and detection circuitry, as well as the servomechanism which eliminates background heating effects from the data, were simultaneously inoperative. The complexity of the interfaces between these devices delayed diagnosis and repair. We now plan to investigate thermal diffusivity in freely suspended thin film samples (two to twenty layers thick), prepared by the method pioneered in this laboratory.[3] Thermal relaxations, due to

mechanisms other than conduction within the liquid crystal, degrade the signal in our technique. We studied thermal loss mechanisms and determined that, at standard atmospheric conditions, heat loss by convection in the air would dominate thermal relaxation in thin film samples. At the same time, temperature uniformity and stability of ≈1m °K are required for critical experiments. We have designed and are now constructing an evacuated double oven to meet these specifications. We will also measure heat capacity in bulk and multilamella 40.8 samples. In addition, we plan to investigate thermal diffusivity in the permeation mode. This mode, in which thermal transport occurs normal to the smectic layers, has not yet been observed.

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I.11 Defects in Liquid Crystals. S. Asher and P.S. Pershan, Contracts N00014-75-C-0648 and NIH 5-R01-GN-24,081-02; Research Unit 4.

We have continued systematic study of the formation of defects in lipid water systems. In addition to the parabolic focal conic structures described last year we have analyzed other defects. We have also elucidated the conditions under which lipid samples will deteriorate chemically during the alignment procedure. This work was published in the *Biophysical Journal.*[1]

Reference

1. S.A. Asher and P.S. Pershan, "Alignment and Defect Structures in Oriented Phosphatidylcholine Multilayers," *Bio. J.*, 27, p. 393 (1979).

I.12 Elastic Properties of Liquid Crystals. M. Fisch, L. Sorenson, and P.S. Pershan, Contracts N00014-75-C-0648, NSF DMR76-22452, and NSF DMR77-24295; Research Unit 4.

The experimental apparatus to measure surface modes in liquid crystals has now been perfected to the point where we can quite readily see capillary waves in isotropic and nematic liquid crystals. Sensitoids and signal-to-noise are up to what is expected theoretically. Under these circumstances we began investigating the light scattering of thermally driven surface waves in the smectic phases. Unfortunately it now seems clear that high frequency surface waves that would be derived from second sound propagation have too low an amplitude to be detected if one depends on thermal processes to excite the wave. Consequently these waves, if they are to be observed, will have to be in a driven mode. Plans are being made to adapt our system to this. On the other hand, it does appear as though there is a thermally driven mode at low frequencies ($1 \sim 2$ Hz) that does have sufficient amplitude to be detected and we are currently pursuing this. In addition, we have clearly seen thermally driven surface waves in the nematic phase of a number of liquid crystals. Previous to our work the only published results on this effect were accomplished in a laboratory in France in which the entire experiment was built on a large granite slab in a basement laboratory. Using an optical heterodyne technique in which the reference signal is derived from the free surface we have managed to reduce the

sensitivity to room vibrations to the point that we are now obtaining equivalent results in our third floor laboratory.

I.13 Light Scattering from Thin Smectic Films. L. Sorenson and P.S. Pershan, Contacts N00014-75-C-0648, NSF DMR76-22452, and NSF DMR77-24295; Research Unit 4.

We have initiated a series of light scattering experiments to look at orientational fluctuations in thin smectic films as the films undergo a transition from what is essentially a two-dimensional liquid crystal to a two-dimensional solid. Preliminary measurements indicate a very definite slowing down of the director fluctuations at this transition. Present efforts are directed towards evaluating the reproducibility of these results, improving sensitivity, and temperature control.

I.14 Raman Scattering in Liquid Crystals. S. Asher and P.S. Pershan, Contracts N00014-75-C-0648 and NIH 5-RO1-GN-24, 081-02; Research Unit 4.

We had successfully learned how to make single crystals of dipalmitoyl phosphatidyl choline-water mixtures for a narrow range of conditions. Polarized Raman spectra have been taken on some of these samples. In the next months we will take more data and complete analysis of these results. The results will then be compared with similar measurements taken at higher temperatures and higher water content where the samples are essentially liquid crystalline.

II. QUANTUM ELECTRONICS

Personnel

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II.1 Nonlinear Four-Wave Mixing in Vapors. M. Dagenais, A. Bogdan, and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 5.

The work on coherent resonant Raman lineshapes has been continued and invited papers on this subject were presented at the 2nd USA-USSR Light Scattering Symposium, New York, May 1979[1] and at the 4th International Conference on Laser Spectroscopy, Rottach-Egern, Germany, June 1979.[2] Invited review papers were also presented at the 14th European Congress on Molecular Spectroscopy, Frankfurt, Germany, September 1979.[3]

Very detailed predictions were made by us about the influence of collisions on coherent resonant Raman lineshapes.[4,5] It was predicted that coherent signals can be enhanced by incoherent collision processes. With further refinements and increased efforts in coherent Raman spectroscopy, it is important to verify these finer predictions. This was done by four-wave mixing in atomic Na vapor in the presence of a buffer gas (He). A nitrogen laser pumped two or three dye lasers and the frequencies

were chosen in the vicinity of the excited states separation $3P_{1/2} - 4D$ and $3P_{3/2} - 4D$. Unfortunately, it appeared that the intensity of the predicted signal would be about 10-100 times smaller than our sensitivity would allow us to measure, but in attempting these measurements, we came across a very interesting effect. We were able to produce a coherent signal by increasing the pressure of the buffer gas. This effect was very similar to the effect we wanted to generate. By judiciously choosing the frequencies of our three dye lasers, we were able to unravel the processes governing the generation of this coherent signal. We proved that this coherent signal was generated in two steps. First, an optical collisionally assisted transition populates the $3P_{1/2}$ and $3P_{3/2}$ state and second, a coherent Raman signal is generated from the excited state. In the absence of collision with a buffer gas, there is no transfer of population to the $3P_{1/2}$ or $3P_{3/2}$ states and no coherent signal is generated. A detailed description of this work will be published shortly.

There is still no complete agreement on the sign of some of the damping factors.[6] There is considerable activity in resonant Raman scattering among chemical and biological scientists, but the systems under study do not permit an unambiguous check of the theory, since they have a complex vibrational structure with unresolved resonances. For these reasons lineshapes of coherent resonant antistokes signals are usually investigated in a vapor of In, a system of well-defined energy levels. We are looking for destructive interference between the resonant CARS and resonant CSRS terms. A new dye laser and a high temperature heat pipe have been constructed and the experiment is now in progress.

For detailed lineshape studies, a c.w. dye laser system with more sharply defined frequencies was purchased and installed. While nonlinear

mixing in Na vapor has been achieved with this system, the major application will be the two-photon absorption measurements in rare earths described in the next section.

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2. N. Bloembergen, "Recent Progress in Four-wave Mixing Spectroscopy," in *Laser Spectroscopy IV*, Proc. 4th International Conference, Rottach-Egern, June 1979, H. Walther and R.W. Rothe (eds.), Springer Series in Optical Sciences, Springer-Verlag, New York, Heidelberg, Berlin.

3. N. Bloembergen, "Stimulated Raman and Two-photon Absorption Processes in Molecules," in *Proceedings of the 14th European Congress on Molecular Spectroscopy*, Frankfurt, 3-7 September 1979 (also in a special volume of *Journal of Molecular Structure*), Elsevier, Amsterdam, to be published.

4. N. Bloembergen, H. Lotem, and R.T. Lynch, Jr., "Lineshapes in Coherent Resonant Raman Scattering," *Indian Journal of Pure and Applied Physics*, 16, 151 (1978).

5. N. Bloembergen, "Stimulated Raman Effect and Coherent Raman Scattering," *Proc. of the Sixth International Conference on Raman Spectroscopy*, edited by E.D. Schmid, R.W. Krishman, W. Riefer, and H.W. Schrotter (Heyden, Philadelphia, 1978), p. 335.

6. L.A. Carreira, L.P. Goss, and T.B. Malloy, Jr., "Comparison of the Coherent Anti-Stokes and Coherent Stokes Raman Lineshapes of the ν_1 Line of β-carotene Near a One Photon Resonance," *J. Chem. Phys.*, 69, 855 (1978).

II.2 Two-Photon Absorption in Rare Earths. M. Dagenais, R. Neumann, M. Downer, and N. Bloembergen, Contract N00014-75-0648; Research Unit 5.

It has been known for a long time that rare earth ions imbedded in a crystal, and even in a liquid, have very narrow transitions linewidths even at room temperature. It is well established that these sharp lines come from barely allowed intraconfigurational 4j - 4f transitions. The 4j electrons in the lanthanide series are deeply buried inside the atom and are effectively shielded from any outside perturbations by the $5s^2\ 5p^6$ closed-shell configuration. While an enormous wealth of spectroscopic data is available from linear absorption spectroscopy, information derived from two-photon excitation techniques is almost absent. Rare earths are very important technological materials and thus there is great interest in their nonlinear optical properties.

As a starting point, it was decided to study Gd^{3+} ion because it has long been known that it fluoresces strongly in the UV. Gadolinium was dissolved in water and attempts made to excite the first excited state ($6P_{7/2}$) at 3100 Å by 2-photon absorption. It was soon recognized that the UV fluorescence was quenched by the water molecules. For this reason, we switched to a crystal of LaF_3 slightly doped ($\simeq$ 0.5%) with gadolinium. In a very successful experiment it was possible to see all the crystal field levels of the $6P_{7/2}$, $6P_{5/2}$ and $6P_{3/2}$ states by detecting the UV fluorescence at 3100 Å. We were thus able to demonstrate the first intracavity, intraconfigurational two-photon absorption in a rare earth doped crystal (and a report will be presented at the APS Spring Meeting in New York[1]). Measurements were performed at ambient, liquid nitrogen, and liquid helium temperatures. The inhomogeneous linewidth of our $LaF_3{:}Gd^{3+}$

crystal was measured to be about 1 cm^{-1} at 77 K; its homogeneous linewidth should be extremely small given the fact that the lifetime of Gd^{3+} is almost 10 msec. All these measurements were performed with the c.w. laser system recently purchased with JSEP funds.

A search for higher excited states will continue for a more complete study of relative two-photon absorption cross-sections. Some of the beautiful spectroscopic techniques developed for atomic systems will continue to be applied to our $LaF_3:Gd^{3+}$ crystal (or others) in order to measure the non-linear properties of the rare earth ions and to gain more knowledge on their interaction with the crystal lattice.

Reference

1. M. Dagenais, R. Neumann, M. Downer, N. Bloembergen, and W.M. Yen, "CW Intracavity Intraconfigurational Two-Photon Absorption of Gd^{3+} in LaF_3," A.P.S. Meeting, New York City, March 1980.

II.3 Picosecond Laser-induced Melting and Resolidification Morphology in Si. P.L. Liu, R. Yen, and N. Bloembergen, Contract N00014-75-C-0648 and NSF Grant DMR 77-24295; Research Unit 6.

Picosecond laser pulses at 532 and 266 nm wavelength were used at intensity levels up to 15 GW/cm^2 to induce ultrafast heating and cooling on the surface of silicon single crystals. Under these experimental conditions, a layer of Si on the order of a few hundred Ångstroms can be heated to above the melting point and subsequently cooled at a rate of 10^{13} °C/sec. Knowing that the maximum crystal growth rate is about

10^4 cm/sec, amorphous silicon formation should be expected.

Optical microscopy and electron diffraction studies on irradiated regions of crystalline silicon indeed revealed the formation of amorphous phase. Details of surface morphology are sensitive functions of pulse intensity, energy, wavelength and crystallographic orientation. But an amorphous silicon formation threshold intensity of several GW/cm^2 is expected for all crystal faces. At higher intensities, an amorphous ring with a recrystallized center is observed.[1]

Under similar experimental conditions, formation of polycrystalline regions is observed when amorphous silicon samples were irradiated by picosecond laser pulses above a certain threshold intensity.

Presently, in collaboration with Professor Turnbull's group, the possibility of forming amorphous regions on polycrystalline metallic samples are under investigation.

Reference

1. P.L. Liu, R. Yen, and N. Bloembergen, "Picosecond Laser-Induced Melting and Resolidification Morphology on Si," *Appl. Phys. Lett.*, 34, 864 (1979).

II.4 Multiphoton Photoelectric Emission. R. Yen, J.M. Liu and N. Bloembergen, Contract N00014-75-C-0648; Research Unit 6.

Photoelectron emission may be classified as either the surface effect or the volume effect depending upon whether the potential step at the surface or the periodic potential within the solid acts as the

momentum absorber. Using picosecond laser pulses we have performed measurements on four-photon photoelectric emission from tungsten. The incident angle and polarization dependence of the photocurrent on the incident light wave has been used to separate the surface effect contribution from the bulk.[1]

Efforts are presently underway to improve the sensitivity of our system. Subsequently, a systematic investigation of multiphoton photoemission from metallic and semiconducting solids will follow.

Theoretical models for multiphoton photoemission predicted deviation from simple power law dependence of the photocurrent as a function of light intensity under high intensity irradiation. This has been observed in our experiment[1] and will be investigated further.

A tunable picosecond optical parametric oscillator has been built[2,3] and will be used for future experiments.

References

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2. P. Liu, "Synchronously Pumped $LiNbO_3$ Optical Parametric Oscillator," *Appl. Optics*, 18, 3543 (1979).

3. P. Liu, "Parametric Generation of Single Picosecond Tunable Pulses," *Appl. Optics*, 18, 3545 (1979).

11.5 Laser-Plasma Interaction. Paul Kolodner and Eli Yablonovitch, Contracts N00014-75-C-0648 and ED-78-S-02-4631; Research Unit 7.

In resonance absorption (RA) of laser light by plasmas, the most important plasma parameter is the density-gradient scale length. We have found that the imposition of an externally produced density gradient on a gas-breakdown plasma has profound effects on the interaction between the light and the plasma. This has allowed RA to be studied largely in isolation from other plasma phenomena. In our experiment, the density structure is that of a shock wave produced in an electrothermal shock tube filled with deuterium. Our principal diagnostic has been the suprathermal electrons emitted parallel to the plasma density gradient vector by the breaking of plasma waves generated in the critical layer.[1]

When a short laser pulse ($t = 100 - 500$ psec) is focussed on a shock-front, suprathermal electrons are emitted from the plasma along the shock-front density gradient (i.e., along the shocktube axis) in numbers greater by a factor of 10 than produced in optical breakdown of homogeneous gas. We have also observed, using photographic film, that the electrons are emitted in a narrow cone along the shock tube axis. These are the signatures that, in this experiment, the target is optimized for RA, and that this interaction has been largely isolated from the hydrodynamics of plasma formation.

The collimation of the emitted hot electrons has allowed their energy spectrum to be analyzed by a magnetic field from a small permanent magnet. An array of charge collectors, multiplexed with an oscilloscope, allows real-time acquisition of the spectrum. Typically, 10^9 electrons are collected, with a temperature 27 keV, when a 50 mJ, 100 psec laser pulse is

focussed at 2×10^{14} W/cm^2 onto a shockfront in 50 torr D_2. The hot-electron temperature is a very weak function of laser intensity and of pressure. This is evidence of density-profile steepening by the ponderomotive force, an effect which is expected for laser intensities greater than 10^{14} W/cm^2.

The experimental portion of this study is essentially complete and has been presented at the 1979 Gordon Conference on Laser-Matter Interaction and the 1979 APS Plasma Physics Division Meeting. In addition, a theoretical paper on the production of large magnetic fields by laser plasmas has been published.[3]

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2. Paul Kolodner and Eli Yablonovitch, *Bull. APS*, 24, (1979).

3. Paul Kolodner and Eli Yablonovitch, *Phys. Rev. Lett.*, 43, 1402 (1979).

II.6 Time Resolved Infrared Double Resonance Spectroscopy. R. Sharp and E. Yablonovitch, Contracts N00014-75-C-0648, N00014-78-C-0531, and ED 78-S-02-4631; Research Unit 7.

The possibility of performing mode selective laser chemistry has received much attention by physical chemists in recent years. The feasibility of such work is critically dependent upon the time necessary for intramolecular vibrational relaxation to occur within a molecule. To

answer the question of how long it takes for a molecule to redistribute energy initially contained in one vibrational mode to other vibrational modes, we are using advanced laser techniques particular to our laboratory; these techniques were discussed in Annual Progress Report No. 92 in Section I.5, and as explained there, the work on Intramolecular Vibrational Relaxation in Polyatomic Molecules has developed into two distinct projects. The first, which uses an infrared-infrared double resonance technique, is reported in this section. The second, which uses an infrared-visible double resonance technique, is reported in the following section.

Present experiments are an extension of the work described in Reference 1. Specifically, our recent results, obtained using a standard pump and probe technique involving a single CO_2 laser, placed an upper limit of 30 psec for the redistribution time from the initially excited ν_3 mode of SF_6. Presently, two CO_2 lasers have been synchronized, and the short (30 psec) infrared pulses produced from each laser allow the infrared spectrum of SF_6 to be pumped and probed at independent wavelengths. A recently completed computer interface of the experiment (see previous section) allows fast data acquisition and an improved signal-to-noise ratio. The double resonance spectrum obtained from SF_6, and other molecules, will hopefully help to answer pressing questions concerning the possibility of mode selective laser chemistry.

Reference

1. H.S. Kwok and E. Yablonovitch, "Collisionless Intramolecular Vibrational Relaxation in SF_6," *Phys. Rev. Lett.*, 41, 745 (1978).

II.7 Internal Molecular Energy Redistribution Induced by Collisionless Infrared Multiphoton Pumping of Gas-phase Molecules, J. Tsao, I. Burak, E. Yablonovitch, Contract 100014-75-C-0648; Research Unit 7.

Using an infrared-visible double resonance system based on our picosecond CO_2 laser pulses and a ruby pumped dye laser system, we have investigated the infrared multiphoton effect in NO_2 and biacetyl. In NO_2, we were able to induce the first known infrared multiphoton pumping of an excited electronic state, and made an important estimate of the resulting vibrational energy distribution, as described in a recent paper.[1]

In biacetyl, we established that a similar effect occurs in its excited triplet state, as well as the additional phenomenon of inverse electronic relaxation. This phenomenon represents a new and important class of radiationless relaxation processes of great interest in physical chemistry; a forthcoming paper describes our work.[2]

Future work is planned on CrO_2Cl_2 and other molecules, in which a more complete infrared multiphoton induced vibrational energy distribution may be determined.

References

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2. J. Tsao, J.G. Black, E. Yablonovitch, and I. Burak, *J. Chem. Phys.* (to be published).

II.8 Multiphoton Vibrational Excitation. J.G. Black and E. Yablonovitch, Contracts N00014-75-C-0648, N00014-78-C-0531, and ED 78-S-02-4631; Research Unit 7.

The question of how isolated polyatomic molecules can absorb the 30 or more vibrational quanta necessary for dissociation is the central focus of the fields of laser-induced chemistry and laser isotope separation.[1] The experimental work done in our laboratory[2] on SF_6 and the physical model developed to explain these results have gained wide acceptance, particularly the picture of rapid randomization of absorbed energy among all the vibrational degrees of freedom of molecules.

Most of the SF_6 work was done during the previous reporting period; the focus since then has been to extend those results to larger and smaller molecules i.e., molecules with greater and lesser densities of vibrational states. In general, the predicted behavior is observed: Molecules with richer vibrational spectra (e.g., $(CF_3)_2CO$) display little or no laser intensity dependence of their multiphoton infrared absorption; smaller, less complicated molecules (e.g., CF_3I) show a marked dependence on laser intensity. SF_6 represents an intermediate case with respect to these two extremes. The construction of an innovative computer automation facility has been completed. This system facilitates rapid data acquisition with extremely high accuracies and several similar systems modeled after it are now in use for other projects in our Quantum Electronics area. The design and construction of this facility will be published shortly.[3]

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2. J.G. Black, P. Kolodner, M.J. Schultz, E. Yablonovitch, and N. Bloembergen, "Collisionless Multiphoton Energy Deposition and Dissociation of SF_6," *Phys. Rev.*, A19, 704 (1979).

3. J.G. Black, "A Simple, Low-Cost Laboratory Computer Interface System," (Scheduled for publication May, 1980, *Review of Scientific Instruments*).

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

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III.1 Nonlinear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

The modeling of nonlinear input-output systems using bilinear systems has been developing over the past few years. In Ref. 1 Wong takes this development a bit further. A natural class of Volterra series is found to admit a universal bilinear realization over a Banach space. Furthermore, there is a canonical way of constructing a minimal realization from this universal realization. The results thus generalize similar results of realization theory of infinite dimensional linear systems, suggesting possible connections among bilinear realization, nonlinear

scattering and the theory of models of operators. The fact that it is possible to construct a universal realization on a space related to Fock representations of quantum mechanics gives added interest to these ideas.

Reference

1. W.S. Wong, "Volterra Series, Universal Bilinear Systems and Fock Representations," *Proc. Thirteenth Annual Conference on Information Sciences and Systems*, Princeton, New Jersey, 1979.

III.2 Estimation Theory. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

In Ref. 1 we continue our work on nonlinear estimation problems. In particular we describe new classes of problems which have easily implementable optimal solutions. Some of these examples are strongly nonlinear and thus fall outside the scope of the standard Kalman-Bucy theory and its recent extensions. The main tool here is the use of Lie algebras to classify various equivalent problems. One attractive feature of this circle of ideas is that they can be used without solving nonlinear differential equations.

Reference

1. R.W. Brockett, "Classification and Equivalence in Estimation Theory," *1979 Conference on Decision and Control*, IEEE, N.Y., 1979.

III.3 Linear Systems. R.W. Brockett, Contract N00014-75-C-0648; Research Unit 8.

In our paper[1] we have developed the idea that the problem of placing the poles of a linear system by output feedback is actually equivalent to a well known problem in geometry which was studied by Shubert and many of his followers. Shubert's studies show, for example, that there are typically very many gains which achieve the desired pole placement if we count complex solutions and that for certain families of problems the problem of placing poles by real output feedback can always be solved. We have also given a rather general explanation of why pole placement with real feedback gains is sometimes impossible. Our results include as special cases many earlier studies.

Reference

1. R.W. Brockett and C.I. Byrnes, "On the Algebraic Geometry of the Output Feedback Pole Placement Map," *1979 Conference on Decision and Control*, IEEE, N.Y. 1979.

Publications:

1. R.W. Brockett and C.I. Byrnes, "On the Algebraic Geometry of the Output Feedback Pole Placement Map," *1979 Conference on Decision and Control*, IEEE, N.Y., 1979.

2. R.W. Brockett, "Classification and Equivalence in Estimation Theory," *1979 Conference on Decision and Control*, IEEE, N.Y., 1979.

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5. W.S. Wong, "Volterra Series, Universal Bilinear Systems and Fock Representations," *Proc. Thirteenth Annual Conference on Information Sciences and Systems*, Princeton, New Jersey, 1979.

III.4 Approaches to Resource Allocation in Large-Scale Systems. Y.C. Ho, R. Suri, and L. Servi, Contracts N00014-75-C-0648, N00014-79-C-0776, and NSF Grant ENG 78-15231; Research Unit 9.

As the size of Large-Scale Distributed Systems continues to grow, the problem of efficient allocation of resources in such systems is becoming increasingly crucial. We have studied and developed two novel approaches to this problem. Both approaches have departed significantly from conventional methods, and have introduced interesting conceptual as well as practical implications.

The first approach involved identifying a certain class of problems called Resource Management problems, and using decentralized solution methods for this class of problems. This approach was begun and described previously (JSEP Progress Report No. 92). During this year we have further refined and extended our techniques for solving Resource Management problems, leading to new theoretical results[1] as well as efficient solution algorithms.[2] Our approach has made possible the solution of very large problems, previously considered unmanageable. Study is continuing on the application of these techniques to the problem of Optimization and Real-Time Control of large, complex Flexible Manufacturing Systems.

The second approach studied a new class of iterative resource allocation algorithms, Center-Free algorithms, which have properties that make them desirable for a large scale system: the algorithms have minimal information requirements and, unlike all other centralized or decentralized resource allocation algorithms, they have the distinguishing characteristic of completely eliminating the need for a coordinating center.[3] To better understand the properties of decentralized and Center-Free algorithms we have investigated a one-to-one correspondence between these algorithms

and some electrical networks. This permits the use of intuition and knowledge of electrical networks to learn more about the algorithms.

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2. R. Suri and Y.C. Ho, "Resource Management for Large Systems," *IEEE Transactions on Automatic Control*, to appear.

3. Y.G. Ho, L. Servi, and R. Suri, "A Class of Center-Free Resource Allocation Algorithms," *Journal of Large Scale Systems*, to appear, 1980.

III.5 Data Base System and Query Processing. Y.C. Ho and D.M. Chiu, Contracts N00014-75-C-0648 and N00014-79-C-0776; Research Unit °.

The work on query optimization described last year has been brought to fruition. In a distributed data base, query processing can be thought of in three parts:

i) local processing at each site,

ii) intersite movement of data,

iii) final assembly of the answer at the target site.

While (i) and (iii) are to a great extent determined by the given query, part (ii) is the major area that requires optimization. In fact, it is typical to assume that the cost for (i) and (iii) are either negligible or fixed. It is the movement of data among site that are costly and time consuming.

We have established that the class of equi-join queries can be divided into two subclasses. The first class called *tree queries* can be processed by a "short" semi-join program consisting only of moving joining

columns of relations among different sites. For the other class, called *cyclic queries*, there may not exist a semi-join program to process the query or the program may be arbitrarily long.[1]

A general optimization methodology has been worked out for optimizing tree queries.[2] In particular for the subclass of chain queries, explicit properties of optimal programs are derived.[3]

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2. D.M. Chiu and Y.C. Ho, "A Methodology for Interpreting Tree Queries into Optimal Semi-Join Expressions," *Proceedings of the 6th SIGMOD Conference*, May 1980, to appear.

3. Dah-Ming Winston Chiu, "Optimal Query Interpretation for Distributed Databases," Ph.D. Thesis, December 1979.

III.6 Teams and Organization. Y.C. Ho and N. Papadopoulos, Contract N00014-75-C-0648 and NSF Grant ENG 78-15231; Research Unit 9.

Over the last year, research has been directed towards two areas. One has been the exploration of internal organizational models incorporating boundedly rational agents. The other has been the application of non-zero-sum differential game theory to the problem optimal capacity expansion in a growing oligopolistic market.

The work in internal organization consists of two short notes both published by the *IEEE Transactions on Automatic Control*.[1,2] The reports both start from the premise that team theory as developed by Marshak and Radner is an intriguing but inadequate approach to solving the problem of optimally organizing the firm. The main inadequacy is the assumption

that the decision makers (agents) are capable of inifinite calculations on any amount of information presented them. Both papers attempt to supplement the team theoretic model of the organization by suggesting a model of a *bounded rational* decision maker: one who attempts to be rational, but has limited capability to process information. One report actually sets a hard bound on the amount of information that the decision maker can read; the other report models the decision maker as one who reacts to informational loading by randomizing his "best" decision. A couple of interesting results are demonstrated when these models are applied to simple examples.

The work in the application of nonzero-sum differential game theory to a problem in growing markets represents an application of nonclassical control to economics. Reference 3 represents an analytic improvement over a model presented by Spence.[5] Through the use of nonzero-sum differential games, the problem of optimal capacity expansion can be solved in a unified fashion. Spence had previously discovered two solutions to the problem; using this technique, his two solutions have been identified as manifestations of information phenomena predicted in the theory of nonzero-sum differential games. Furthermore, interpretations have been made which place the problem in the context of Schelling's concept of flexibility, information in nonzero-sum games, and other forms of economic and game theoretic analysis.

A long survey article on team theory and information structures was also written at the invitation of IEEE.[6]

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III.7. Differential Games and Incentive. Y.C. Ho, G.J. Olsder, and P. Luh, Contract N00014-75-C-0648, NSF Grant ENG 78-15231, and Bolt Beranek and Newman , Inc. -8094; Research Unit 9.

The scientific activities during this period were mainly focused on two topics: a survey on differential games and research on incentive controllability.

The subject of Differential Games has been in existence for about twenty-five years. A very large body of literature has been built up, scattered about many journals. The aim of the survey was to provide an introduction to the subject and to give the reader a guide to further reading. About 350 references were collected and put into a systematic order. The organization of the many Russian contributions took considerable time. The survey primarily treats the deterministic, zero-sum case, in which two schools can be distinguished: the Isaacs school (USA, started mid-fifties) and the Russian school (Pontryagin, Krasovskii, started late sixties). Extensions to the nonzero-sum and/or stochastic games are briefly discussed,

specifically the many new concepts that arise in these extensions.

The notion of incentive controllability is related to a nonzero-sum differential game, in which the players have conflicting, though not purely opposite, interests. The roles of the players are not identical; there is one leader, the other(s) is (are) followers. Examples are: the electricity company (the leader) states tariff rules for electricity use and the consumers (the followers) decide how much electricity to use; the government (the leader) states certain tax laws and the people (the followers) decide how much money to earn (there is a trade-off between working a longer time and having free time). Incentive controllability addresses the problem of how powerful the leader is; can he influence the follower such that he, the follower, behaves as the leader would like him to do? This problem becomes particularly interesting (and harder) in a stochastic environment in which the follower has certain information which the leader does not have. The latter direction is closely related to the so-called Groves-mechanisms in economy, which have to do with problems of coordinating and controlling divisions of a large firm. These divisions are rather independent and may have local information that the corporate headquarters does not have.

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III.8 <u>Production Line as Discrete Event Dynamic Systems.</u> Y.C. Ho, and M.A. Eyler, Contract N00014-75-C-0648 and NSF Grant ENG 78-15231; Research Unit 9.

The work reported in the previous year has been brought to a successful conclusion. We have developed a complete and practical method to improve the productivity of a transfer line, either at the design stage or for an existing line. The approach, being a combination of analysis and experimentation, is fundamentally different than the existing methods. The gradient information of the line productivity with respect to any decision variable is made available by an observation of the system through time. (The observation can be made on the actual line for real time, as well as on a simulation model of the line.) The method is based on answering the basic question "what would happen if a small change was made on a decision variable?" without actually making the change. The importance of the method is its ability to answer a number of such questions for different variables *simultaneously*, i.e., in just one observation; thus, the experimentation time is reduced significantly.

Two applications of the method were presented: First, the problem of the optimal buffer allocation in a transfer line was solved using an algorithm based on the gradient information with respect to buffer sizes. Then, measures of criticality were developed in order to evaluate the critical points of a line quantitatively, again using the gradient information.

The importance of this method lies in the fact that we have managed to develop a linearization technique for discrete event discontinuous dynamic system. Extension and generalization of this linearization technique to more general systems is being studied.

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III.9 Stochastic Realization Theory. P.E. Caines and D. Delchamps, Contract N00014-75-C-0648; Research Unit 10.

A stochastic realization for a wide sense stationary process y consists in the representation of y as the output of a (possibly finite dimensional) linear state space system driven by a stationary orthogonal process. One is interested not only in carrying out all such constructions but also in classifying and interrelating them. A sequence of workers has studied this problem over recent years (see e.g., Akaike,[1,2] Lindquist and Picci, *et al.*[3,4,5]). In particular, the notion of a (minimal) splitting subspace between the past and future of a process has been introduced. Such a space summarizes all the information concerning the past behavior of a process needed for prediction of its future and so plays the role of a stochastic state space. The crucial feature of this type of space is its intrinsic construction from the process to be realized. In our work[6] we give a general theory of splitting subspaces and then use them to construct all possible intrinsic stochastic (state space) realizations of a given process y. When y has a rational spectral density these realizations are classified in a way that reveals their one-to-one correspondence with both the set of all stable spectral factors of minimal degree and the set of all solutions to the Positive Real Equation (PRE). This relationship between stchastic realizations, spectral factors and solutions to the PRE

is believed to illuminate an important structural characteristic of stationary stochastic processes. In particular the theory has applications to system modeling and identification and to process filtering and smoothing.

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III.10 Stochastic Adaptive Control. P.E. Caines and D. Dorer, Contracts N00014-75-C-0648 and NASA NCC 2-39; Research Unit 10.

Our initial results on stochastic adaptive control (see references 1,2 and the references therein) demonstrated the existence of simple adaptive control laws which stabilize the output behavior of linear deterministic and stochastic systems whose parameter values are unknown. Current

research on this topic is concerned with the extension of these results to larger classes of control algorithms and the derivation of adaptive control laws for systems with randomly varying parameters. Connections between these problems and the theory of passive deterministic and stochastic systems are being investigated.[3]

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IV. ELECTROMAGNETIC PHENOMENA

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Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Most practically significant problems in this area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are conveniently grouped under two main headings, viz., *antennas and waves in and over dielectric, conducting, and plasma media*, and *antennas in air*. The first group is concerned with the circuit, radiating, and scattering properties of antennas and arrays and the waves generated by them in their dependence on the electrical properties of a

material medium (lake water, sea water, earth, ice, living tissue, plasma, etc.) in various forms and degrees of proximity. The antennas may be directly embedded in the medium or separated from it by a layer of insulation. The second group of investigations deals with the detailed electrical properties of complicated metal radiating and scattering structures in air including especially electrically thin and thick crossed conductors used to model an aircraft.

ANTENNAS AND WAVES IN AND OVER DIELECTRIC, CONDUCTING, AND PLASMA MEDIA

IV.1. Theoretical and Experimental Study of the Scattering from an Obstacle Above the Earth. H.-M. Lee and T.T. Wu, Contracts DAAG29-79-C-0109 and N00014-75-C-0648; Research Unit 11.

The electromagnetic field scattered by objects located above water has been studied theoretically and experimentally.

Using a thin-strip loop as the target, we were able to write down the integral equations governing the two components of the surface current on the loop excited by an external field. The kernels of the integral equations have been separated into two parts, one that contains just the kernels for the equations of a loop in free space, and another that contains parameters describing the electromagnetic properties of water as a function of the distance of the loop from the water surface and so represents the interaction between the current in the loop and that in the earth.

The free-space kernels have been expanded successfully in powers of the width of the strip. This has enabled us to devise an iterative procedure to calculate the excited surface current on the loop when the loop is in free space. After having taken care of the square-root divergence of the

surface current at the edge of the loop, we made use of a Fourier series expansion along the width of the loop and generated iteratively each Fourier coefficient to all orders.

With the exact solution for the loop in free space at hand, it is reasonable to assume that the solution of the problem of a loop above water takes the same form, but with modified Fourier coefficients.

Some major improvements in the experimental system have been made during this reporting period. A new tube was put into the power generators. An absorbing wall was installed to shield the measuring equipment from the electromagnetic field radiated by the antenna. The setup was then used to carry out an extensive study of the field scattered from crossed wires of different sizes and types in free space.

Measurements of the scattered field from a loop above water are underway. Of particular interest is the behavior of the scattered field from loops of various sizes at different heights above the water. Some results for the scattered field from each of a set of eighteen loops with circumference varying from one-half wavelength to more than one-and-a-half wavelengths have been obtained.

IV.2. Scattering by a Thin-Wire Cross. R.W.P. King, H.-M. Lee, and B.H. Sandler, Contracts N00014-75-C-0648 and DAAG29-79-C-0109; Research Unit 11.

The currents and charges induced in a right-angled cross of thin wire have been determined analytically when the arms of the cross have arbitrary lengths but the exciting field is normally incident.[1] They have also been determined when the active field is incident at an arbitrary angle but only

for the equiarm cross and *only in zero-order*.[2] This approximation does not take account of the effect of cross coupling. Work is in progress to obtain a first-order solution for the currents in a cross with arms of arbitrary lengths and with the active field incident at an arbitrary angle.[3] A recent investigation of the cross in a normally incident field has shown that the odd mode of oscillation, i.e., from the vertical into the horizontal arms, is very sensitive to the lengths of the arms when these are near resonance. A detailed study of this effect at other than normal incidence is planned since it is of considerable significance in problems relating to the bistatic scattering by crossed wires. Measurements of the scattered field will also be made.

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IV.3. Numerical and Analytical Determination of Electromagnetic Fields of Antennas in the Earth Near Its Interface with Air. R.W.P. King, B.H. Sandler, and L.C. Shen, Contract N00014-75-C-0648; also NSF Grant ENG-76-17596 with the University of Houston; Research Unit 11.

The calculation of the electromagnetic field in a dissipative half-space due to an infinitesimal electric dipole in the same half-space and with

its axis parallel to the interface is a classic problem closely related to the work of Sommerfeld on the field in air due to a dipole also in air above a dissipative earth. It has been the subject of extensive investigations. In an earlier paper,[1] expressions for the three cylindrical components of the electric field were obtained from Baños' general formulas in terms of complex integrals. These were evaluated numerically for a range of frequencies and radial distances from a horizontal dipole in sea water, lake water, and dry earth. An alternative derivation that proceeds directly from Maxwell's equations and the boundary conditions[2] has led to equivalent integral expressions. These have been evaluated by a less time-consuming program; as a result, more comprehensive calculations have been possible. Tables have been prepared of the generally useful, radial component of the electric field for radial distances from .1 m to 100 km, frequencies from 10 to 10^9 Hz, effective relative permittivities ε_{er} from 20 to 80, and effective conductivities σ_e from 4×10^{-6} to 4 Si/m. In a paper recently accepted for publication[3] three practical ranges of the parameters are selected for careful study and interpretation. These are dry earth ($\varepsilon_{er} = 4$, σ_e = 0.00004 to 0.04 Si/m), moist earth ($\varepsilon_{er} = 20$, σ_e = 0.0004 to 0.4 Si/m), and water ($\varepsilon_{er} = 80$, σ_e = 0.004 to 4 Si/m). Extensive graphs and contour diagrams of E_ρ serve to display the characteristics of propagation in their dependence on the frequency, the radial distance, the depth, and the electrical parameters of the earth. They are interpreted in terms of the approximate formulas of Baños which are evidences of the lateral-wave nature of the field.

For actual transmission, antennas of finite size are required. The problem of determining the field of a finite antenna in or above a dissipative half-space is difficult since it involves not only the shape and

dimensions of the antenna, but also the conducting and dielectric properties of the earth. The field generated by the currents in an extended conductor can be calculated from the known field of an infinitesimal dipole only after the distributions of current have been determined in their dependence on the properties of the earth. In a recent paper[4] three special cases of a horizontal wire in or close to a dissipative earth have been studied. These are an end-driven Beverage-type antenna, a horizontal wire as a scatterer in the presence of the earth, and an embedded insulated traveling-wave antenna.

In a related study[5] special attention is given to the eccentrically insulated traveling-wave antenna embedded beneath the surface of the earth. This antenna is particularly useful for subsurface communication by lateral waves since its field pattern is highly directive upward. Simple analytical formulas for the input impedance, current distribution, and field pattern are derived that incorporate the recent advances in determining the properties of antennas of finite size in the presence of the air-earth boundary. A step-by-step procedure for designing an eccentrically insulated traveling-wave antenna is given. To increase the directivity further, a broadside array of eccentrically insulated traveling-wave antennas can be used.

Since lateral-wave transmission is inefficient even when fairly directive eccentrically insulated traveling-wave antennas are used, relatively large amounts of power must be supplied to the antenna in order to generate a significant field at a distance. The question arises: How intense is the field radiated upward into the air? Is this sufficiently intense to be hazardous to living organisms? This is the subject of a recently published paper,[6] in which accurate calculations are made of the electric and magnetic

fields in the air above a horizontal electric dipole successively located in the sea, a lake, and the earth. This is carried out directly from the exact general integrals. Useful approximate expressions for the field in air above the transmitting dipole are also obtained which indicate that the limiting forms given by Baños are oversimplified for the determination of the phases. Numerical calculations from the exact formulas are also made of the electric and magnetic fields on the surface directly over the embedded dipole, and approximate simple formulas are derived and compared.

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IV.4. Lateral-Wave Propagation and Modeling of the Lithosphere. M.F. Brown, J.T. deBettencourt, R.W.P. King, L.C. Shen, J.E. Baum, H.M. Shen, and T.T. Wu, Contracts N00014-75-C-0419 and N00014-75-C-0648; Research Unit 11.

An experimental study of lateral-wave propagation along the boundary between salt water and air is in progress. A horizontal shallow tank 8' by 12' in dimensions contains 6" to 8" of salt water. A vertical metal plane at one end effectively doubles the length by providing an image plane. A transmitting monopole projects through it into the water at a small distance below its surface. It is driven by a 600 MHz source with a 40 watt capacity. A horizontal dipole just below the surface and a vertical monopole that projects just above the surface can travel on a carriage the full length of the tank. Their output can be recorded in amplitude and phase to measure the radial electric field in the water and the vertical electric field in the air just above the surface of the water. A metal plane 8' by 12' in dimensions is supported at a variable height above the surface of the water. It can be inclined from the horizontal at arbitrary angles to provide a wave-guide like space between the conducting and dielectric water and a similar image in the metal plane. Although the conditions of electromagnetic similitude are not readily satisfied, the structure does provide a model of the sea, the rocky layer of the lithosphere below it, and of the highly conducting mantle at still greater depths.

After the apparatus has been standardized by comparison of the measured fields with those calculated theoretically,[1,2] studies will be made of the effects of surface layers between the air and the water, and of surface irregularities and discontinuities of various types.

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IV.5 Transmission and Reception with Embedded Bare and Insulated Antennas.

R.W.P. King, S. Prasad Hinchey, and B.H. Sandler, Contract N00014-75-C-0648; Research Unit 11.

Transponders are embedded in or located just outside a living organism for the remote monitoring of various quantities such as body temperature, heart beat, and intensity of radiation. Alternatively, it may be of interest to use an embedded or externally attached transponder to identify or locate animals in their environment. The successful operation of such systems depends greatly on the proper design of transmitting and receiving antennas for use within or near a living organism. For this, it is necessary to know the magnitude, phase and polarization of the electric field at different points of observation in the body and just outside its surface. Furthermore, the complete circuit properties (admittance, current, and charge per unit length) of the embedded or attached antenna are of interest in their dependences on the electrical properties of the environment.

A complete investigation has been reported[1] on the voltage generated by an incident plane wave across the load of a bare or insulated receiving dipole at various depths in a half-space composed of a single homogeneous material with the electrical properties of skin. This includes the determination of the impedance of the antenna in the particular environment.

The reciprocal problem of obtaining the voltage across the load in a receiving antenna located at a distant point in air by an emf applied to a bare or insulated dipole embedded at various depths in a half-space of skin has also been solved.[2] Specifically, two-way communication between an element embedded up to 1 cm in skin and an outside unit at a distance of 4.3 m at the optimum frequency of 700 MHz or 1 m at 3 GHz has been analyzed. The solution of the electromagnetic problem of the transponder at various depths in a homogeneous half-space of skin is thus completed.

A further investigation has been made[3] to extend these analyses to receiving and transmitting antennas located in or near the surface of a three-layered half-space consisting of finite thicknesses of skin and fat on an infinite depth of muscle. In particular, the properties of bare and insulated antennas are examined when successively located in the air just outside the body and at the centers of the layers of skin and fat, and at a fixed distance in the muscle. The electromagnetic problems that require solution for the centrally loaded receiving antenna include the determination of the following quantities: (a) The electric field at all points where a transponder may be located in terms of the incident field at the surface of the skin. (b) The driving-point impedance Z_0 of the bare and insulated antennas when located successively in the air and in the layers of skin, fat, and muscle. (c) The current in the load for both types of antenna in each of the four locations. (d) The voltage V_L across the load Z_L. For the transmitting mode, the additional quantity required is the ratio $|V_L|/|V^e|$ of the voltage V_L across the load of the receiving antenna in air to the driving voltage V^e applied across the terminals of the embedded transmitting antenna. Bare and insulated antennas are considered over a frequency range up to 3 GHz with layer thicknesses of skin from 0.1 to 1.0 cm,

and of fat from 0 to 1.5 cm. The application of the results to finite bodies is discussed.

An experimental and theoretical study is in progress on the properties of insulated antennas embedded at a considerable depth below the surface of a living organism or of the earth. Methods of transmitting power for localized radiation or heating are under study.[4] These include series-connected sections that successively and selectively make use of transmitting and radiating properties, insulated folded dipoles, and choke sections of insulated conductors.

For efficient and highly localized heating in a dissipative medium like a tumor in a body or parts of the earth, four-element structures of coupled insulated antennas arranged in a square are under investigation. The driving-point admittances and current distributions with three different phase sequences are of interest since they have different near-field properties and hence behave differently with regard to the localized transfer of power to the ambient medium.

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IV.6. Theoretical and Experimental Study of Electromagnetic Fields and Antennas in Dissipative and Dielectric Cylinders. R. Bansal, Contract N00014-75-C-0648; Research Unit 11.

The investigation of the electromagnetic fields inside a finite dielectric cylinder illuminated by an incident plane wave has been advanced substantially. The major effort has been focused on the measurement of the axial (z) and transverse (ϕ) components of the induced electric field. Since the phase is often a more sensitive variable in the interpretation of the standing-wave patterns, the distribution of the electric field was measured in phase as well as in amplitude.

The finite dielectric cylinder used in the experiment consisted of a styrofoam container filled with water. The "effective" water column was 50 cm in height and had a radius of 8.65 cm. The first set of measurements was made at 100 MHz ($k_0 h = \pi/6$, where k_0 is the free-space wave number and h is the half-length of the cylinder) in distilled water. The spatial variation of the electric field in the cylinder was found to be sufficiently slow to indicate the feasibility of measurements at higher frequencies. Measurements were then carried out at 300 and 600 MHz ($k_0 h = \pi/2$ and π, respectively), again with distilled water in the styrofoam container. The data at 600 MHz show the standing-wave nature of the electric-field distribution very clearly.

After the measurements in distilled water (corresponding to the lossless dielectric case) were completed for the three different frequencies, it was decided to extend the study to the case of a dissipative dielectric cylinder. The conductivity of water was gradually increased from approximately zero to 3.5 Si/m by adding salt to the distilled water. The constitutive parameters (ϵ_r, σ) of each salt solution used in the experiment were carefully measured at each frequency with the help of a coaxial-line

setup developed previously at Harvard.[1] The electric-field measurements in salt-water solutions have been completed at 100 and 300 MHz and are currently in progress at 600 MHz.

The incident field (in the absence of the dielectric cylinder) in the vicinity of the cylinder was measured with a movable surface-charge probe on the ground plane supporting the dielectric cylinder. Measurements of the incident field at 100 and 600 MHz have been completed, and they affirm the approximately plane-wave nature of the incident field, generated by a quarter-wave monopole with a corner reflector.

On the theoretical side, two numerical approaches have been investigated with respect to the finite cylinder of water. The so-called extended boundary-condition method used by Barber[2] was found to be rather limited in scope in its application to the salt-water cylinder because the complex argument Bessel functions used by him in the expansion of the internal field tend to be singular for large permittivities. The volume integral equation formulated by Livesay and Chen[3] has shown more promise and will be investigated further, along with other possible methods.

A paper summarizing the measurement techniques and the data obtained so far has recently been submitted for presentation.[4]

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IV.7 Experimental Studies of Antennas in Plasmas. M.J. Miller and D. Preis (now at Tufts University), Contract N00014-75-C-0648; Research Unit 11.

The performance of a cylindrical antenna of half-length h in a material medium depends on both βh and α/β. In a plasma medium α/β and β are indirectly related to the ratio of the operating frequency ω to the plasma frequency ω_p and the ratio of the collision frequency ν to ω_p. Changing the operating frequency of a plasma-immersed cylindrical antenna within a 10 to 1 range can change β more than 3 orders of magnitude while the α/β ratio can easily vary throughout the range $0 < \alpha/\beta < 100$. In a conference paper presented during the year,[1] a preliminary report was made of the measured impedances and distributions of current and charge of antennas in a plasma. A comparison of the experimentally obtained data with the corresponding theoretically calculated quantities is in preparation. Use is being made of the general theory for a cylindrical antenna in a homogeneous, isotropic, dissipative medium[2] which applies to antennas of electrical length βh from zero to more than 2π immersed in a medium whose α/β ratio can vary from zero to 10.

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1. D. Preis, M.J. Miller, and R.W.P. King, "The Cylindrical Antenna in a Plasma Medium: A Critical Comparison of Experiment with Theory," presented at the 1979 IEEE International Conference on Plasma Science, held in Quebec, Canada, on June 4-6, 1979.

2. R.W.P. King, B. Sandler, and T.T. Wu, "Cylindrical Antennas Immersed in Arbitrary Homogeneous Isotropic Media," *J. Appl. Phys.*, vol. 40, pp. 5049-5065, December 1969.

IV.8. Antennas in Matter: Fundamentals, Theory, and Applications. R.W.P. King, M. Owens, and T.T. Wu, Contracts N00014-75-C-0648, F19628-76-C-0057, and F44620-72-C-0021, and NSF Grant ENG 75-14455; Research Unit 11.

The results of current and past researches, supported by the above Contracts and Grant, on bare and insulated antennas in and over dissipative or dielectric media have been integrated into a three-part book manuscript now in the proof stage.[1] Part I is devoted primarily to the simple, transmission-line-like behavior of the insulated antenna in a relatively dense medium. A brief introduction is also given to the bare antenna in an approximate, quite simple form. Both types of antenna are then studied as probes in material media; the propagation of plane waves and pulses in such media is subsequently treated. Part II is an advanced theoretical treatment of antennas in various media. It begins with a detailed study of the electromagnetic equations in homogeneous, isotropic media including the careful formulation of constitutive relations. The complete theory of the bare dipole in a general medium is presented and this is followed by a rigorous analysis of the insulated antenna. Similar analyses are provided for the bare and insulated loop antennas. The concluding chapter in Part II treats

the problem of subsurface communication between antennas near the plane interface between air and a general half-space. Finally, Part III is concerned with the construction of experimental models and the techniques of measurement relating to antennas and probes in a general dissipative or dielectric medium.

Reference

1. R.W.P. King, G.S. Smith, M. Owens, and T.T. Wu, *Antennas in Matter: Fundamentals, Theory, and Applications*, The M.I.T. Press, Cambridge, MA, 1980 (in press).

ANTENNAS IN AIR

IV.9 Single and Crossed Electrically Short and Thin Tubular Cylinders. R.W.P. King, D.J. Blejer, and B.H. Sandler, Contract N00014-75-C-0648 and Grant AFOSR-76-3073; Research Unit 11.

The surface densities of current and charge induced on tubular, highly conducting cylinders and intersecting cylinders by a normally incident plane wave depend in both their axial and transverse distributions on the length and radius of the individual conductors. When $ka \le 0.1$, the general series of transverse Fourier components is well approximated by two terms for both E- and H-polarizations. When $kh > 1$, $ka \le 0.1$, the zero-order axial current dominates and thin-cylinder theory and junction conditions are adequate to determine the axial distributions. In a recently published paper[1] it is shown that, as kh is reduced to satisfy the conditions $ka < kh << 1$, the magnitude of the rotationally symmetric axial current decreases to small values and the first-order axial currents

together with the transverse currents dominate. All of these have non-rotationally symmetric transverse distributions. They are determined by the local incident magnetic field and are in a large measure independent of junction conditions.

Reference

1. R.W.P. King, D.J. Blejer, and B.H. Sandler, "Current Induced on Single and Crossed Electrically Short and Thin Tubular Cylinders by a Normally Incident, Plane Electromagnetic Wave," *IEEE Trans. Antennas Propagat.*, vol. AP-27, pp. 624-633, September 1979.

IV.10 Surface Currents and Charges Induced on Electrically Thick Cylinders, Crossed Cylinders, and Cylinders Crossed with Horizontal Flat Plates by an Incident Plane-Wave Field. R.W.P. King, D.J. Blejer, and R.W. Burton, Contract N00014-75-C-0648 and Grant AFOSR-76-3073; Research Unit 11.

The experimentally determined distributions of current and charge induced by a normally incident plane electromagnetic wave on all of the surfaces of a metal cross formed by a vertical tubular cylinder and a horizontal flat plate are the subject of a recently published paper.[1] The cylinder was a wavelength in circumference and 1.75λ high over a large ground plane. The horizontal plate consisted of two equal arms that extended 0.75λ from the surface of the cylinder; it was 0.2125λ wide, 0.0255λ thick, and was centered at a height of 1.25λ above the ground plane. The distributions were compared with the corresponding ones on crossed tubular cylinders and on isolated cylinders. In general, the currents and charges on a horizontal flat plate are less closely coupled to the currents and charges on the vertical cylinder than are those on a horizontal cylinder.

The distributions are relatively simple, and are a useful approximation of the surface currents and charges induced on an aircraft.

Reference

1. R.W.P. King, D.J. Blejer, and R.W. Burton, "Surface Currents and Charges on an Electrically Thick Cylinder and a Flat Plate in a Normally Incident, Plane-Wave Field," *Radio Science*, vol. 14, pp. 753-763, September-October 1979.

IV.11 Electromagnetic Fields and Currents and Charges on Cylinders in a Parallel-Plate Transmission Line. R.W.P. King, D.J. Blejer, T.T. Wu, R.W. Burton, M.E. Burton, and H.M. Shen, MRC Subcontract SC-0082-79-0009 and Contract N00014-75-C-0648; Research Unit 11.

In order to determine the magnitudes and distributions of currents and charges induced on the surfaces of an aircraft when it encounters an electromagnetic pulse generated by a nuclear explosion, large simulators have been constructed in which the aircraft can be exposed to a hopefully comparable electromagnetic environment. One important type consists of a parallel-plate transmission line or open waveguide with tapered triangular ends, between the conductors of which a pulse with a plane wave front must travel. Since the relevant pulse contains a frequency spectrum with wavelengths that extend from very long to relatively short compared to the dimensions of the aircraft, the separation of the two conductors of the transmission-line simulator cannot be kept small compared to all of the wavelengths in the pulse as required for TEM transmission without propagating higher modes. It follows that TEM-mode transmission line theory can be applied only to the very low frequency part of the spectrum. The properties of the simulator at higher frequencies are difficult to determine accurately. One approach is to measure the electric field in a

model simulator at one or more of the relevant higher frequencies, and then seek to interpret its distribution theoretically. This has been done in a carefully designed model simulator at a frequency of 625 MHz.[1] When, as in this case, the frequency is so high that the electrical height kh is not small compared to one, most of the energy supplied by the generator is radiated into the surrounding space, and only a small fraction is dissipated in the load. The structure is essentially an antenna and not a transmission line.

Direct measurements were made of both the amplitude and phase of the vertical (E_z) and longitudinal (E_y) components of the electric field throughout the working volume (regions between the parallel plates), and of E_z on the surfaces of both conducting plates where $E_y = 0$. In order to interpret the measured results, the field in the working volume was represented approximately in terms of the mode theory of the infinite parallel-plate waveguide. For the operating wavelength $\lambda = 48$ cm, four modes are well above cut-off. They are the TEM, TM_{01}, TM_{02}, and TM_{03} modes. Comparisons with the measured data indicate that the assumed approximate representation of the field by the superposition of ideal parallel-plate modes is a good one throughout the working volume of the simulator. It is also evident that the total E_z differs greatly from the part contributed by the TEM mode alone. This is true particularly near the top where the difference between the incident spherical wave in the sloping sections and the plane wave in the working volume is greatest. There is no difference on the ground plane. Note also that the field in the working volume is not a pure traveling wave with constant amplitude, but includes a large standing wave. TE modes contribute only negligibly and are ignored.

Measurements have also been made at a second high frequency, $f = 264$ MHz, where with the separation h between the parallel plates reduced from 108 cm to 75 cm, h is now $.65\lambda$ rather than 2.25λ of the previous case. Now only the TEM and TM_{01} modes are below cut-off. These can be uniquely determined from the longitudinal and transverse components of the electric field. TE modes are neglected. The TEM mode is determined at $z/h = 0.5$ where the vertical component E_z of the electric field of the TM_{01} mode is zero. E_z for the TM_{01} mode is the difference between the total measured E_z and the E_z for the TEM mode. The measured longitudinal component E_y of the electric field belongs entirely to the TM_{01} mode.

Of particular interest is the reduction of the standing waves which are generated in the parallel-plate region by reflections at and beyond the edge of the parallel-plate region. Measurements show that the major part of the standing-wave amplitude at high frequencies is due to the TEM mode. At particular frequencies, e.g., $f = 271$ MHz, with $h = 75$ cm, the TM_{01} mode can combine with the TEM mode to produce localized, very deep minima that correspond to standing-wave ratios of between 15 and 30. The maxima are unaffected since the amplitude of the TM_{01} mode is relatively small. The effect arises from nearly equal and opposite imaginary parts of the TEM and TM_{01} waves at a point where the real part of the TEM wave has a zero. Experimental and theoretical studies are in progress on methods to reduce the standing-wave ratio in the parallel-plate region including that due to the deep minimum.

Since the field in a simulator may differ appreciably from that maintained by a traveling plane-wave pulse, the effect of such differences on the currents and charges induced on an aircraft or missile is of interest. Measurements to determine the differences induced currents and charges

between those generated by an incident plane wave and by the actual distribution in a model simulator are planned as an application and continuation of the earlier study of thin and thick cylinders and crossed cylinders in the absence of the simulator (previous heading).

Reference

1. R.W.P. King and D.J. Blejer, "The Electromagnetic Field in an EMP Simulator at a High Frequency," *IEEE Trans. Electromagn. Compatib.*, vol. EMC-21, pp. 263-269, August 1979.

V. SIGNIFICANT ACCOMPLISHMENTS REPORT

V.1 Laser-Induced Thermal and Thermoelectric Effects in Superconducting Tunnel Junctions. A.D. Smith, W.J. Skocpol, and M. Tinkham; Research Unit 2, SOLID STATE ELECTRONICS.

Superconducting tunnel junctions are useful probes of the non-equilibrium conditions generated in thin films by incident laser light. Energy absorbed from the light is eventually shared among the electrons and phonons in the material, causing changes in the distribution of occupied energy states of the quasiparticle excitations.

By using Al-Al_2O_3-PbBi tunnel junctions for which the current-voltage characteristics are sensitive to the occupation of quasiparticle energy states, we have been able to invert the data obtained from illuminated junctions in order to obtain the nonequilibrium occupation distribution in the aluminum film with unparallelled sensitivity and accuracy.[1] For the case of small departures from equilibrium, the nonequilibrium electron system is quite well characterized by an elevated temperature T^*, and the measured temperature rise is consistent with the observed decrease of the superconducting energy gap. Such behavior is in line with recent theories, but had not been previously shown by direct experiment.

In the course of these experiments, we detected the presence of a small voltage-independent current across the junction associated with the presence of the light. By directly measuring the current across an unbiased junction using a SQUID picoammeter, we have characterized the dependence of this current on both temperature and illumination intensity. The effect

can be explained by a simple model which considers the temperature difference between the two films of the junction caused by the illumination together with energy-dependent tunneling probabilities related to the barrier height in the insulating oxide. This explanation of this newly observed thermoelectric effect in tunnel junctions resolves longstanding discrepancies in several earlier experiments on thermoelectric effects in point contacts with oxide barriers.

Reference

1. A.D. Smith, W.J. Skocpol, and M. Tinkham, *Phys. Rev.* B, to appear.

V.2 Picosecond Laser-Induced Melting and Resolidification. N. Bloembergen and P.L. Liu; Research Unit 6, PICOSECOND NONLINEAR OPTICS.

It is possible to melt or vaporize a thin surface layer of a conductor with a single picosecond pulse. It has been known for several years that this is the primary mechanism for damage of metallic reflecting surfaces by short pulses. The absorption depth in good conductors at visible and near infrared wavelength is about 10 to 40 nm, or $(1 \text{ to } 4) \times 10^{-7}$ cm. Here the laser energy is absorbed, and during a pulse of 10^{-11} sec or less there is no appreciable heat diffusion into the interior substrate. Thus, a molten layer can be created on top of the original substrate which remains near room temperature. The thermal gradient has an order of magnitude of 10^{10} °C/cm. After the end of the laser pulse, very rapid cooling and resolidification occurs. The initial cooling is almost as rapid as the heating, and cooling rates of 10^{14} °C/sec may be obtained.

We have observed this phenomenon utilizing picosecond pulses at 0.53 μm and 0.26 μm wavelength on a single crystal of silicon.[1] The amorphous phase can be created and is observed by its higher optical reflectivity and by electron diffraction. The details of the morphology are quite sensitive to the duration of the laser pulse, its wavelength, crystal face orientation and other parameters. The amorphous layer may be remelted by a second pulse. If this second pulse has a longer duration, a single crystal may regrow. Thus, an amorphous-crystalline solid state optical switch may be obtained with a sub-nanosecond time response. This may be important for optical information processing.

It appears that a new field of materials research is opening up with ultrafast cooling rates of 10^{14} °C/sec. Thus, almost any liquid alloy composition may be frozen into an amorphous solid surface layer. New aspects in metal, semiconductor and surface physics can be explored, concerned with picosecond time scale phenomena in atomic motions, phase transitions and relaxation effects.

Reference

1. P.L. Liu, R. Yen, N. Bloembergen, and R.T. Hodgson, *Appl. Phys. Lett.*, 34, 864 (1979).

V.3 New Results in Nonlinear Filtering. R.W. Brockett; Research Unit 8, INFORMATION ELECTRONICS: CONTROL AND OPTIMIZATION.

The estimations of positions and velocities of aircraft based on noisy radar data is but one example of many which may require the use of rather sophisticated data reduction techniques for a satisfactory solution. Over

the past 15 years the Kalman-Bucy filter has become the standard tool for solving these kinds of problems in those areas where accuracy is important. However, most problems do not fit the conditions for which the Kalman-Bucy solution is known to be appropriate because of nonlinearity. This has given rise, over the years, to a great deal of work whose goal is to understand nonlinear estimation problems. Our recent work[1,2] makes a contribution to this problem and has produced a significant change in the way people are now thinking about this problem. In particular, we now have a systematic way to generate examples of nonlinear estimation problems whose solutions are easily implementable.

The technique we have introduced is a logical outgrowth of our work on nonlinear systems based on Lie algebraic methods. The idea is to classify the complexity of a nonlinear estimation problem in terms which are independent of particular choices of coordinates and in this way achieve an intrinsic measure of complexity. Using these methods we have conducted new classes of systems whose optimal filers can be computed explicitly even though they are nonlinear.

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1. R.W. Brockett, "Remarks on Finite Dimensional Estimation Theory," *Astérisque* (to appear).

2. R.W. Brockett, "Classification and Equivalence in Estimation Theory," *Proceedings of IEEE Conference on Decision and Control*, Dec. 1979.

V.4 <u>New Results on Multivariable Feedback Compensation</u>. R.W. Brocket; Research Unit 8, INFORMATION ELECTRONICS: CONTROL AND OPTIMIZATION.

Most control systems which call for advanced methods are multivariable with significant interactions between the variables being controlled. Even in the case of linear systems, this interaction can make the design of feedback compensations very difficult. The question of adjusting the natural frequencies of the system by gain feedback--the multivariable version of the root-locus problem--is a specific problem in this area which has proven to be quite difficult to understand conceptually or computationally. In our recent papers,[1,2,3] we have shown that this problem and related ones can be thought of as specific instances of a class of problems in geometry having a very long and episodic history beginning around 1880 with the work of Shubert and continuing to this day.

Specifically, we have been able to show that in those cases where the number of gain parameters equals the number of poles to be placed. It is possible to actually serve the poles using real values for the gain in certain exceptional cases. In the typical situation the polynomial equations which define the appropriate gains have a very large number of solutions (we calculate this number) and this seems to explain why convergent algorithms for finding the gains are hard to design. Equally important is the fact that in general the solutions of these equations may all be complex even though the systems are given in terms of real numbers. We have given some results which describe this case in detail.

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2. R.W. Brocket and C.I. Byrnes, "On the Algebraic Geometry of the Output Feedback Pole Placement Map," *Proc. of the 18th Conference on Decision and Control, IEEE*, New York, 1979.

3. R.W. Brockett and C.I. Byrnes," Multivariable Nyquist Criteria, Root Loci, and Pole Placement: A Geometric View Point, submitted *IEEE Trans. Automatic Control.*

V.5 Electromagnetic Propagation Along Boundaries. R.W.P. King and T.T. Wu; Research Unit 11, ELECTROMAGNETIC PHENOMENA.

The theory of electromagnetic wave propagation along the plane interface between two half-spaces with electrically different properties has been a subject of interest and extensive study since the early work of Sommerfeld in 1909.[1] Exact general integrals for the fields near the interface in both media due to horizontal and vertical source dipoles have been available for over fifty years and many approximate solutions have been provided, including especially those suggested by Baños.[2] With the advent of high-speed computers, attention was directed toward the numerical evaluation of the complex integrals in order to obtain more accurate results than were provided by the available approximate formulas. Contributions from Harvard specifically to propagation from and to antennas in sea water near the surface included both numerical[3,4] and experimental[5] researches.

A serious shortcoming of numerically evaluated results is that they provide no physical insight into the nature of the phenomena. In order to obtain both understanding and practically useful information about propagation along the various surfaces of the earth--the sea, a lake, earth, etc.--a systematic theoretical, numerical and experimental study was begun. In a preliminary report[6] a fairly extensive set of results was presented.

This has now been extended[7-9] to provide a comprehensive picture of propagation from horizontal electric dipoles in all types of material found in the earth's surface. Included are boundaries between air and materials with permittivities that range from 4 to 80 and conductivities from 4×10^{-6} to 4 Siemens/meter. Also treated are boundaries between rock with the relative permittivity 16 and conductivities ranging from 4×10^{-8} to 4×10^{-3} and sea water such as may be found in the earth's lithosphere. The tabulations and graphs encompass the complete electrically useful frequency range from 10 to 10^9 Hz over distances that range from 10 cm to 100 km.

Of particular significance is the complete theoretical interpretation and explanation of the results in terms of simple approximate formulas that are themselves quantitatively accurate only under restricted circumstances but provide the needed framework for physical understanding. Noteworthy is the description of a high-frequency "window" which offers both a much greater range than that obtainable at very low frequencies and the possibility of constructing directional arrays.

An old problem for which only complicated integrals, approximate formulas, and more or less specialized information have been available, has now been solved completely to provide accurate quantitative results for practical application together with a thorough understanding of the complicated nature of lateral-wave propagation. The latter includes a detailed description of the significance of exponential attenuation with both depth and radial distance and of the different decreases in amplitude with distance in the so-called near, intermediate, and asymptotic ranges.

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